

Pairing-excitation versus intruder states in ^{68}Ni and ^{90}Zr

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Abstract

A discussion on the nature of the 0^+ states in ^{68}Ni ($Z = 28$, $N = 40$) is presented and a comparison is made with its valence counterpart ^{90}Zr ($Z = 40$, $N = 50$). Evidence is given for a 0^+ proton intruder state at only ~ 2.2 MeV excitation energy in ^{68}Ni , while the analogous neutron intruder states in ^{90}Zr reside at 4126 keV and 5441 keV. The application of a shell-model description of 0^+ intruder states reveals that many pair-scattered neutrons across $N = 40$ have to be involved to explain the low excitation energy of the proton-intruder configuration in ^{68}Ni .

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I. INTRODUCTION

The nucleus ^{68}Ni was initially considered as a semi-magic nucleus arising from a major $Z = 28$ proton-shell closure and a $N = 40$ neutron subshell closure. This interpretation was inferred from the high energy of the first-excited 2^+ state (2033 keV [1]) in contrast with the low energy of the first-excited 0^+ state (1770 keV [2]). Conflicting observations arose, however, as mass measurements do not reveal a clear neutron shell gap at $N = 40$ [3, 4] and the $B(E2; 0_1^+ \rightarrow 2_1^+)$ mean value of 3.2(6) W.u. [5, 6] is too large for a pronounced $N = 40$ subshell gap [7].

Currently, it is qualitatively understood that the apparent semi-magic properties of ^{68}Ni are not caused by a strong $N = 40$ subshell closure and a corresponding large energy gap, but rather follow from the parity change between the pf shell and the $1g_{9/2}$ orbital across $N = 40$, prohibiting quadrupole excitations [8]. The $B(E2)$ value is explained by strong pair scattering across $N = 40$ [5], which indicates that the stabilizing effect is subtle.

Despite these qualitative insights, the structure of ^{68}Ni and the region around is not yet fully understood. While the focus was, so far, mainly on neutron excitations across $N = 40$, little is known about proton excitations across $Z = 28$. Although separation energies give evidence for a major $Z = 28$ shell closure at $N = 40$, a proton two-particle-two-hole $\pi(2p-2h)$ 0^+ state could appear nonetheless at lower excitation energies due to pairing correlations and proton-neutron π - ν residual interactions [9–11]. Its excitation energy will depend critically, however, on the stabilizing properties of the $N = 40$ gap as the quadrupole part of the π - ν interaction depends on the number of valence neutron particles or holes.

Since the valence counterpart of ^{68}Ni , ^{90}Zr ($Z = 40$, $N = 50$), is a stable isotope, it has been investigated in numerous transfer reactions and thus its structure is better known than the one of ^{68}Ni . In the present paper, the low-energy structures of both nuclei, and the 0^+ states in particular, are compared based on experimental information available in the literature (see Fig. 1). While most properties are similar in ^{68}Ni and ^{90}Zr , possible $\pi(2p-2h)$ excitations in ^{68}Ni will behave different from the $\nu(2p-2h)$ excitations in ^{90}Zr . In the following, a candidate for a $\pi(2p-2h)$ 0^+ is discussed on the basis of a shell-model approach of intruder states [10], after which implications for the stabilizing properties of the $N, Z = 40$ gaps are discussed.

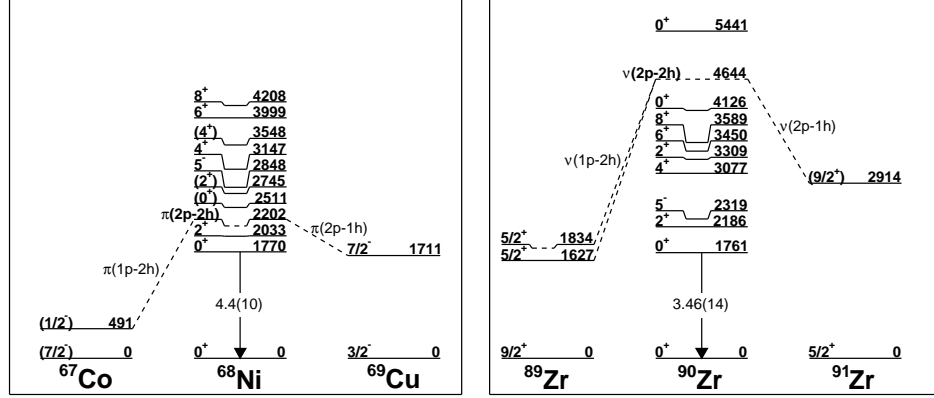


FIG. 1: Low-energy structure of ^{68}Ni and ^{90}Zr [2, 12–14]. The arrows denote $\rho^2(E0) \cdot 10^3$ transition strengths [15]. The estimated excitation energies of the respective π and $\nu(2p-2h)$ configurations, based on $1p-2h$ and $2p-1h$ excitation energies of the $Z \pm 1$ and $N \pm 1$ nuclei [16–22], respectively, are represented by the dashed lines.

II. LOW-ENERGY STRUCTURE OF ^{68}Ni AND ^{90}Zr

A. The active valence nucleons

At low excitation energies, the ^{68}Ni and ^{90}Zr valence nucleons (neutrons and protons, respectively) are expected to be predominantly active in the $2p_{1/2}$ and $1g_{9/2}$ space, and to a smaller degree in the $1f_{5/2}$ and $2p_{3/2}$ space. The energy difference between the $2p_{1/2}$ and $1g_{9/2}$ orbitals constitutes the $N, Z = 40$ energy gap in ^{68}Ni and ^{90}Zr , respectively.

In a simplified picture, the ground state of ^{68}Ni and ^{90}Zr is expected to exhibit a $(2p_{3/2})^4(1f_{5/2})^6(2p_{1/2})^2$ character, while excited 0^+ states could be created by promoting a nucleon pair from the $2p_{1/2}$ or $1f_{5/2}$ to the $1g_{9/2}$ orbital. It has been observed that the 0_2^+ state in ^{68}Ni and ^{90}Zr feature remarkable similarities. Their respective excitation energies of 1770 and 1761 keV are almost identical, as well as their respective monopole $\rho^2(E0)$ transition strengths of $4.4(10) \cdot 10^{-3}$ and $3.46(14) \cdot 10^{-3}$ [15].

Using spectroscopic factors from transfer reactions [23], and mean-square radii $\langle r^2 \rangle_{2p_{1/2}}$ and $\langle r^2 \rangle_{1g_{9/2}}$ determined from the $^{90}\text{Zr}(t, \alpha)^{89}\text{Y}$ reaction [24], the measured $\rho^2(E0)$ transition strength in ^{90}Zr can be reproduced with a simple two-component model allowing for strong $\pi 2p_{1/2}$ (59%) and $\pi 1g_{9/2}$ (41%) configuration mixing [25]. This gives substantial evidence for a strongly mixed 0_1^+ ground state and 0_2^+ excited state. Recent shell-model calculations

confirm these observations [26, 27]. Although the similar $\rho^2(E0)$ transition strength in ^{68}Ni is not understood, the similar excitation energy suggests comparable 0_1^+ and 0_2^+ configurations, involving now the neutrons.

The 0^+ state arising from $(1f_{5/2})^{-2}$ has not been identified in ^{68}Ni nor in ^{90}Zr . The (0_3^+) state, which has been observed in ^{68}Ni at 2511 keV [13], might be a possible candidate, although such a state is not observed in ^{90}Zr in spite of the more extensive spectroscopic information.

The 2^+ , 4^+ , 6^+ , and 8^+ levels in ^{68}Ni at respective excitation energies of 2033, 3147, 3999, and 4208 keV are good candidates for the $g_{9/2}$ $v = 2$ seniority levels. In ^{90}Zr , a similar structure is observed with the respective $v = 2$ seniority levels at excitation energies of 2186, 3077, 3450, and 3589 keV.

B. Intruders across the $Z = 28$ or $N = 50$ gap

The excitation energy of 2p-2h 0^+ intruder states in nuclei at a major closed shell Z (or N) can be estimated from summing the $\pi(\nu)(2p-1h)$ and $\pi(\nu)(1p-2h)$ intruder excitation energies in the $Z + 1(N + 1)$ and $Z - 1(N - 1)$ nuclei [28] (see Ref. [29] for details). Using this prescription, the excitation energies of, e.g., $\pi(2p-2h)$ 0^+ states in $Z = 82$ lead and $Z = 50$ tin nuclei are generally reproduced within 100 keV.

In ^{89}Zr , it is shown by the $^{91}\text{Zr}(p,t)$ reaction [20] that the $\nu(1p-2h)$ configuration is mainly distributed over two states at excitation energies of 1627 and 1834 keV [12]. The $^{88}\text{Sr}(\alpha,n\gamma)$ [21], (p,p') , and $^{92}\text{Zr}(p,d)$ reactions [22] show that the major fraction of the $\nu(2p-1h)$ configuration in ^{91}Zr resides in the 2914-keV state [12]. By using the above mentioned prescription and averaging the excitation energies of the two $\nu(1p-2h)$ ^{89}Zr levels, an expected excitation energy of 4644 keV for the $\nu(2p-2h)$ state in ^{90}Zr can be deduced. The situation is depicted by the dashed lines in Fig. 1.

It has been shown by a $^{92}\text{Zr}(p,t)$ reaction [14] that the $\nu(2p-2h)$ configuration is mainly concentrated in the 0^+ states at 4126 and 5441 keV excitation energy. The average of both excitation energies is 4784 keV, which differs only by 140 keV from the estimate.

The same reasoning can be applied to ^{68}Ni . The $\pi(2p-1h)$ character of the 1711-keV level in ^{69}Cu is suggested by a large spectroscopic factor in the $^{70}\text{Zn}(d,^3\text{He})$ reaction [17] and a small $B(E2)$ transition strength to the ^{69}Cu ground state observed in Coulomb excitation

[19]. From a recent ^{67}Fe β -decay study [16], the $\pi(1p-2h)$ state in ^{67}Co was identified at 491 keV, giving rise to an estimated excitation energy of the $\pi(2p-2h)$ 0^+ state in ^{68}Ni at only 2202 keV.

A good candidate for a $\pi(2p-2h)$ 0^+ configuration would be the (0_3^+) state in ^{68}Ni , which is also a possible candidate for a $\nu 1f_{5/2}^{-2}$ state. From the presently available experimental data, however, it is not possible to differentiate between the two possible configurations. Although extremely challenging, future transfer and multi-Coulomb-excitation experiments can deliver crucial information to investigate this state and other low-energy levels in ^{68}Ni .

In spite of their very similar excitation spectrum, there is thus a large difference in excitation energy of the 2p-2h intruder states across $Z = 28$ or $N = 50$ in respectively ^{68}Ni and ^{90}Zr . The possible reasons for this difference will now be investigated.

III. SHELL-MODEL DESCRIPTION FOR 2p-2h 0^+ STATES IN ^{68}Ni AND ^{90}Zr

The 0_2^+ excitation energies in ^{68}Ni and ^{90}Zr suggest nearly identic structures of their 0_1^+ and 0_2^+ states. On the other hand, the summed excitation energy of the $\pi(1p-2h)$ and $\pi(2p-1h)$ levels in ^{67}Co and ^{69}Cu , respectively, is very different from the $\nu(2p-2h)$ excitation energy in ^{90}Zr . The shell-model approach of Ref. [10] provides a quantitative description of $\pi(2p-2h)$ and $\nu(2p-2h)$ 0^+ states, which can explain this apparent paradox in ^{68}Ni and ^{90}Zr .

A. Framework and results

Intruder states result from particle-hole excitations across major closed shells. Nevertheless, they appear at low excitation energy because of both strong pairing and π - ν correlations. For the 2p-2h 0^+ intruder states, this is expressed [10] as

$$E_{intr}(0^+) = 2(\varepsilon_p - \varepsilon_h) - \Delta E_{pairing} + \Delta E_{\pi\nu}, \quad (1)$$

where $E_{intr}(0^+)$ is the excitation energy of the 0^+ intruder state, $\varepsilon_p - \varepsilon_h$ the single-particle shell-gap energy with the respective subscripts p and h denoting particles and holes, $\Delta E_{pairing}$ the nucleon pairing energy, and $\Delta E_{\pi\nu}$ the π - ν residual-interaction energy.

The shell-gap and pairing energies for ^{68}Ni and ^{90}Zr are deduced from measured one- and two-nucleon separation energies [3, 30] (see Ref. [10] for details). Starting from the

experimental 2p-2h 0^+ excitation energies, the respective π - ν residual energies can be extracted, using equation 1. These values are listed in Table I. It is important to note that the $E_{intr}(0^+)$ values in the table are subject to mixing, and no transfer data are known for ^{68}Ni . The excitation energy of the ^{90}Zr $\nu(2\text{p-}2\text{h})$ configuration, e.g., is taken as the average of the 4126- and 5441-keV levels, which are strongly populated in the $^{92}\text{Zr}(p,t)$ reaction [14].

TABLE I: ^{68}Ni and ^{90}Zr are compared starting from their $E_{intr}(0^+)$ values arising from 2p-2h excitations across the indicated neutron and proton gaps. Also the corresponding $\varepsilon_p - \varepsilon_h$, $\Delta E_{pairing}$, and $\Delta E_{\pi\nu}$ values are compared.

Isotope	Gap	$E_{intr}(0^+)$ (keV)	$\varepsilon_p - \varepsilon_h$ (keV)	$\Delta E_{pairing}$ (keV)	$\Delta E_{\pi\nu}$ (keV)
^{68}Ni	$Z = 28$	2202 ^a	5270(320)	4500(700)	-3838(1000)
^{68}Ni	$N = 40$	1770	3050(100)	4705(14)	380(200)
^{90}Zr	$Z = 40$	1761	2670(90)	3593(8)	20(190)
^{90}Zr	$N = 50$	4126	4445(8)	4093(12)	-670(20)
		5441	4445(8)	4093(12)	640(20)
		av. 4784	4445(8)	4093(12)	-10(20)

^aEstimate from summing $\pi(2\text{p-}1\text{h})$ and $\pi(1\text{p-}2\text{h})$ excitation energies.

The extracted π - ν residual-interaction energy mainly results from quadrupole correlations. Fig. 2 shows a schematic representation of the quadrupole π - ν energy ΔE_Q [10] as a function of neutron (proton) number between the closed shells at $N(Z) = 28$ and $N(Z) = 50$ assuming two extreme cases: $Z(N) = 40$ is a closed (dashed lines) and open (full line) shell configuration. In the latter case, the contribution of quadrupole correlations is strongest around $N = 39$, and intruder states are expected lowest in excitation energy. On the other hand, if $Z(N) = 40$ represents a shell closure, the contribution of quadrupole correlations becomes negligible around $Z(N) = 39$, and pairing-excitation states at high excitation energy might be observed.

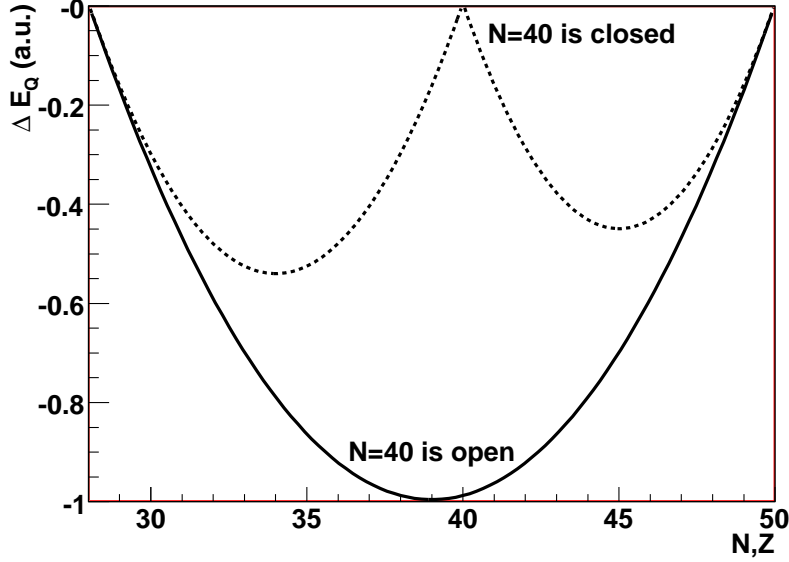


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B. Discussion

The $\nu(2p-2h)$ and $\pi(2p-2h)$ 0^+ states in ^{68}Ni reside at respective excitation energies of 1770 keV and ~ 2.2 MeV, which are rather similar, even though the $Z = 28$ shell gap is about 2.2 MeV larger than the $N = 40$ subshell gap. For both gaps, a large gain in pairing energy (4500 and 4705 keV, respectively) exists. For $N = 40$, it fully explains the low $\nu(2p-2h)$ excitation energy. The low excitation energy of the $\pi(2p-2h)$ state, on the other hand, requires a strong gain in binding energy from the π - ν residual interactions ($-3.8(10)$ MeV). This means that many valence neutrons must be available, i.e., $N = 40$ tends to behave rather as an open shell configuration, as given by the full line in Fig. 2.

As noticed already, the $\pi(2p-2h)$ 0^+ state in ^{90}Zr appears at a remarkably similar excitation energy to the $\nu(2p-2h)$ state in ^{68}Ni . Table I reveals, however, that the larger shell-gap energies at $N = 40$ compared to $Z = 40$ is mainly compensated by a stronger gain in pairing energy. So, although both excitation energies are almost identical, the situations at $N = 40$ and $Z = 40$ are different. Like the $\pi(2p-2h)$ state in ^{90}Zr , the low excitation energy of the $\nu(2p-2h)$ 0^+ state in ^{68}Ni is explained by the gain in pairing energy, which is consistent with a good $Z = 28$ shell closure.

The $\nu(2p-2h)$ configuration in ^{90}Zr is centered at a significantly higher excitation energy (4784 keV) than the $\pi(2p-2h)$ state in ^{68}Ni (2.2 MeV), despite a 0.8-MeV smaller $N = 50$ shell gap and similar pairing energy. This implies a much weaker π - ν residual interactions in the $\nu(2p-2h)$ states of ^{90}Zr : the average excitation energy of 4784 keV is consistent with essentially no π - ν residual interaction. In contrast to $N = 40$ in the nickel isotopes, $Z = 40$ behaves as a closed shell configuration, as depicted in Fig. 2 by the dashed lines.

It can be seen from Table I that the open and closed character as observed in the 0^+ properties of the $N = 40$ and $Z = 40$ subshell is caused by a stronger pair scattering of neutrons across $N = 40$ than protons across $Z = 40$: at $N = 40$, the pairing energy is about 1.65 MeV larger than the shell gap, while at $Z = 40$, this amounts only to about 0.9 MeV. Moreover, the difference in pairing energies compensates the difference in unperturbed shell-gap energies giving rise to almost identical excitation energies of the 0_2^+ states in ^{68}Ni and ^{90}Zr .

In $^{71,73}\text{Cu}$, the $\pi(2p-1h)$ $7/2^-$ levels are identified at 981 and 1010 keV, respectively, based on the particle-core model [18] and the small $B(E2)$ transition strength [19]. This is ~ 700 keV lower in excitation energy with respect to the $\pi(2p-1h)$ state in ^{69}Cu . Extrapolating this trend to the nickel and cobalt isotopes, means that the intruder configuration might reside at even lower excitation energies in $^{70,72}\text{Ni}$ and become even the ground state in $^{69,71}\text{Co}$.

IV. CONCLUSION

The ^{68}Ni and ^{90}Zr low-energy structures have been compared in the framework of $2p-2h$ configurations across the $Z = 28$, $N = 40$ and $Z = 40$, $N = 50$ (sub)shell gaps. The discussion was triggered by recent experimental data obtained in ^{69}Cu [19] and ^{67}Co [16]. Strong similarities are observed between the two valence counterparts, but also important differences. The 0_2^+ states in the respective nuclei feature almost identical excitation energies and monopole $\rho^2(E0)$ transition strengths. Based on the summing prescription of the $\pi(1p-2h)$ and $\pi(2p-1h)$ levels in ^{67}Co and ^{69}Cu , respectively, the $\pi(2p-2h)$ 0^+ state in ^{68}Ni is estimated at only 2.2-MeV excitation energy, while the $\nu(2p-2h)$ 0^+ state in ^{90}Zr is centered around 4784 keV.

In an attempt to understand the origin of this difference in ^{68}Ni and ^{90}Zr , the shell-model description of 0^+ intruder states [10] has been applied. It shows that the excitation energies

of the 0_2^+ states in ^{68}Ni and ^{90}Zr are similar in spite of the difference in the unperturbed single-particle shell-gap energies, as it is compensated to a large extent by the difference in pairing energies. Moreover, it shows that stronger neutron pair scattering in ^{68}Ni gives rise to more active valence neutrons, which strongly interact with proton excitations across $Z = 28$. As a result, the $\pi(2p-2h)$ state in ^{68}Ni is strongly pushed down by π - ν residual interactions by as much as 3.8(10) MeV, while the $\nu(2p-2h)$ state in ^{90}Zr is hardly affected by π - ν residual interactions. These findings highlight the fact that neutron pair scattering across $N = 40$ around ^{68}Ni is far more important than proton pair scattering across $Z = 40$ around ^{90}Zr .

Acknowledgments

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